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The velocity and vorticity fields around an oscillating airfoil in compressible dynamic stall are reported. Phase averaged, two component laser velocimetry data were obtained at a freestream Mach number of 0.3 and a reduced frequency of 0.05. This is the first set of velocity data available at a high Reynolds number (540,000) under compressible flow conditions and it serves as a good database for development and validation of computer codes. Of particular interest is the formation of a separation bubble, which bursts coincidentally with the formation of the dynamic stall vortex, adding an extra degree of physical complexity to the problem.

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Velocity and Vorticity Distributions over an Oscillating Airfoil Under Compressible Dynamic Stall

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Abstract

THE velocity and vorticity fields around an oscillating airfoil in compressible dynamic stall are reported. Phase averaged, two component laser velocimetry data were obtained at a freestream Mach number of 0.3 and a reduced frequency of 0.05. This is the first set of velocity data available at a high Reynolds number (540,000) under compressible flow conditions and it serves as a good database for development and validation of computer codes. Of particular interest is the formation of a separation bubble, which bursts coincidentally with the formation of the dynamic stall vortex, adding an extra degree of physical complexity to the problem.

Contents

The performance of helicopters and the maneuverability of fixed wing aircraft is limited by dynamic stall and the gross separation of the unsteady flow that accompanies it. The dynamic stall flowfield is a complicated combination of a multitude of fluid dynamic effects that include tremendous fluid acceleration around the leading edge formation of strong suction peaks; development of the local boundary layer under strongly adverse pressure gradients; transition of the leading-edge laminar boundary layer, its separation, and reattachment resulting in a separation bubble that grows and eventually bursts just when the dynamic stall vortex forms; under compressibility conditions ($M \geq 0.3$), formation of shock(s) and the induced separation due to it; addition of large amounts of coherent vorticity into the flow and its coalescence into the dynamic stall vortex that later convects over the airfoil upper surface and interacts with the trailing edge separated flow that propagates toward the leading edge; and so on. The complex interactions governing the physical problem have hitherto made understanding the origin of dynamic stall and attempts at modeling the flow very challenging. The study being reported provides a comprehensive set of velocity data along with vorticity distributions derived from it, which can be used to model the flow. In addition, it also serves as a database to verify computational results and enables development of new codes.

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A 7.62-cm-chord NACA 0012 airfoil was oscillated sinusoidally with its angle of attack varying as, $\alpha = 10$ deg-10 deg $\sin \omega t$ at a reduced frequency $[k = (\pi fc/U_\infty)]$ of 0.05 in a flow with a freestream Mach number of 0.3. The details of the wind tunnel used are given in Ref. 1. A standard two component (U and V) frequency shifted laser velocimeter was used for the measurements. Optical encoders mounted on the drive provided the pertinent time-dependent information. A novel approach of freezing the encoder data when coincident U and V velocity samples were present served to provide reliable phase angle data, which were later ensemble averaged by sorting into bins covering 3 deg in phase angle. The velocities were computed for bins containing at least 50 samples. When this condition was not satisfied, suitable interpolation methods were used, if data were found in the neighboring bins. One μm polystyrene latex particles suspended in alcohol were used for seeding the flow. Further documentation of the experimental details can be found in Ref. 2.

Velocity Measurements in the Separation Bubble

Some interesting flow features can be seen in the variation of the horizontal component of velocity U with phase angle ϕ, in Fig. 1, for different heights (y/c) at the streamwise location $x/c = 0.083$. At $y/c = 0.067$, phase angle of 160 deg, $\alpha = 6.6$ deg, the velocity drops rapidly as a separation bubble forms over the airfoil. (It should be noted that the flat portions of the distributions for $y/c = 0.067$ and $y/c = 0.083$ are caused

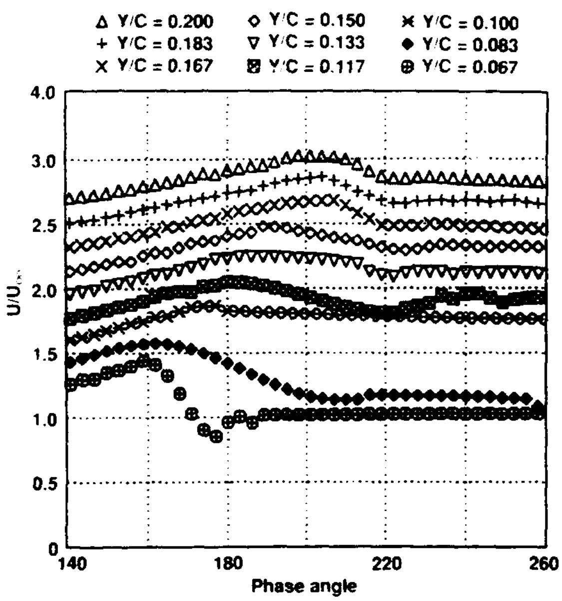

Fig. 1 *U* **component velocity measurements at** $x/c = 0.083$ **(velocity offset by 0.2** (U/U_∞) **for each successive** y/c **location).**

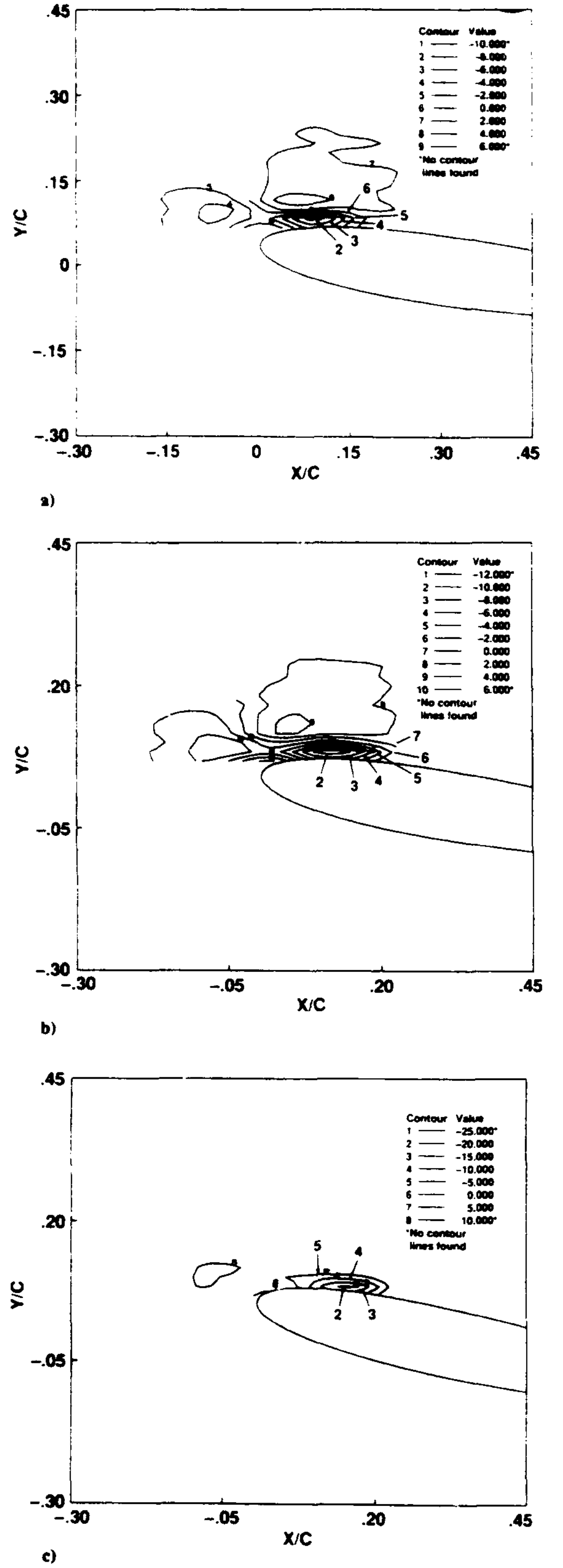

Fig. 2 Contours of normalized z component of vorticity: a) $\phi = 171$ deg, $\alpha = 8.44$ deg, b) $\phi = 180$ deg, $\alpha = 10.0$ deg, and c) $\phi = 198$ deg, $\alpha = 13.09$ deg.

by the blockage of the beams close to the airfoil.) Since the bubble is encountered later in the cycle at a higher y/c point, the phase angle at which the drop occurs increases with y/c. However, at y/c values outside the bubble, the velocity distributions are parallel to each other. This leads to the conclusion that the bubble height is $0.03\,c$–$0.04\,c$ above the airfoil upper surface.

An analysis of the corresponding vertical component of velocity V showed rapid increases in the velocity at $\phi = 200$ deg, $\alpha = 13.4$ deg. This is associated with bursting of the separation bubble. It is worthwhile mentioning that the bubble bursting is somewhat gradual and not as abrupt as is normally perceived.

Vorticity Distributions

The z component of vorticity was calculated from the measured U and V components of velocity by first fitting a cubic spline curve to the data and interpolating the velocities in a grid at a resolution of 1.25 mm, using a second-order central differencing scheme. Thus, the noise level in the distributions is expected to be high at about 20% of the local maximum vorticity values (in both the positive and negative quantities). The following discussion about the vorticity field should still be valid, especially before the dynamic stall vortex begins to convect because no discontinuities such as shocks were encountered within the measurement grid. Thus, the picture of the flowfield is also quantitatively valid up to the point where the particles were able to follow the flow properly.

Figure 2a shows that at $\phi = 171$ deg ($\alpha = 8.44$ deg), a region of clockwise vorticity has developed over the airfoil, just around the location of the separation bubble, with a peak vorticity of -8 units in it. A region of counter-clockwise vorticity could also be found above it, but the peak vorticity within it is only about 5 units. As the airfoil reaches an angle of attack of 10 deg (Fig. 2b) the clockwise vorticity has increased to -11 units, whereas the anticlockwise vorticity is still at 5 units. The extent of the vortical region has grown to about 25% chord in both the x and y directions. As the airfoil pitches to higher angles of attack, the vorticity should increase steadily until the vortex begins to convect. Figure 2c shows that at $\phi = 198$ deg, this is the case as the clockwise vorticity has doubled to -22 units, but the anticlockwise vorticity has only increased to about 10 units. Earlier experiments[3] have shown that the vortex begins to convect at around this phase angle. The separation bubble also bursts around the same angle of attack. Thus, a combined effect is felt by the airfoil, which should be seen in its vorticity field. A calculation of the circulation[2] over the measurement region showed an increase until the stall vortex convection was initiated and dropped slightly beyond this angle of attack.

The study leads to the following conclusions.

1) One of the salient features of the flow is the formation of a separation bubble. This bubble bursts (opens up) just around the angle of attack at which and the location where the dynamic stall vortex forms, complicating the flow physics.

2) The clockwise vorticity was found to increase in the flow until the vortex begins to convect.

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